

Modelling Composite Materials: ANSYS & ACP

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CERN EP-DT-EO

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EP-DT
Detector Technologies

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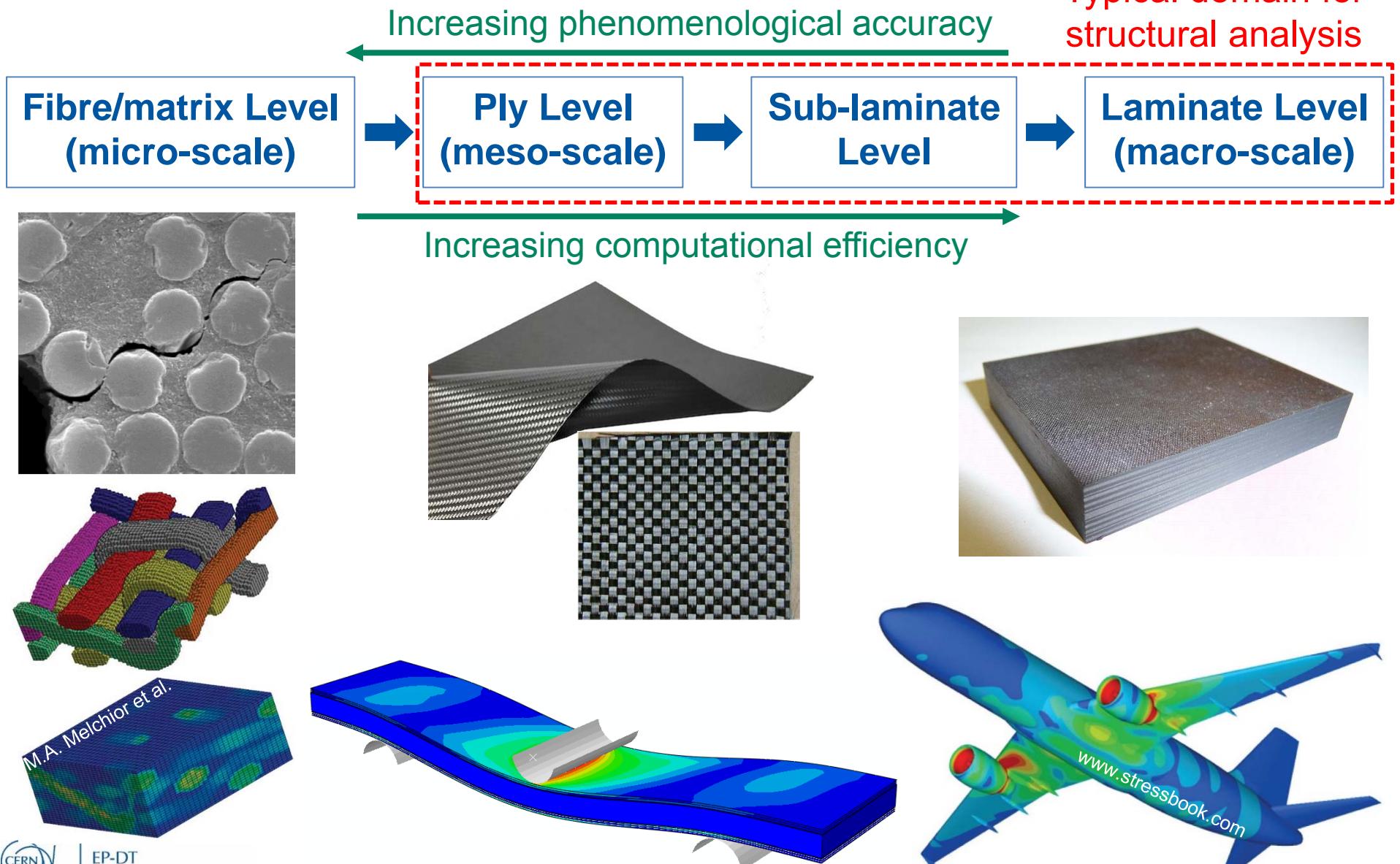
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- Introduction
- Modelling composites in ANSYS WB
- ANSYS Composite PrePost (ACP)
- Modelling Delamination

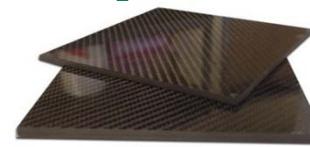
Layered Materials: Analysis Scale

- Laminate Analysis Approach



Laminates: Geometrical Representation

Laminate



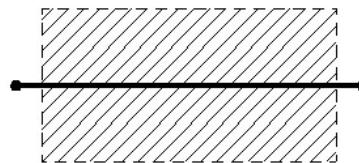
Single through-thickness element

Multiple through-thickness element

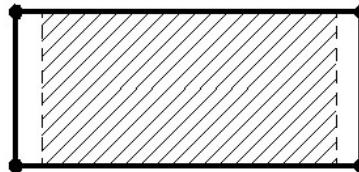
Homogenised Properties

Layered Properties

Shells

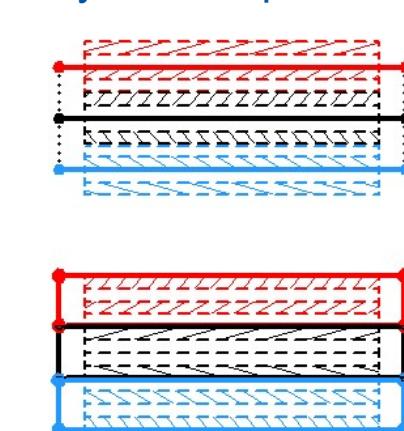
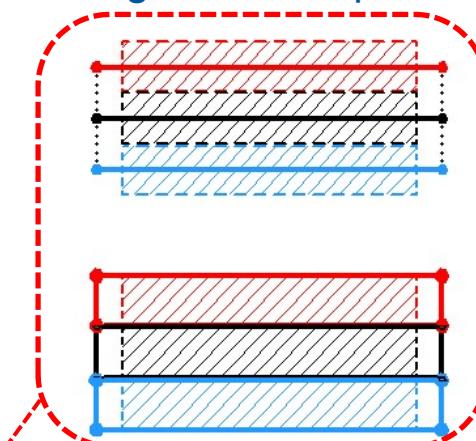


Solids



Homogenised Properties

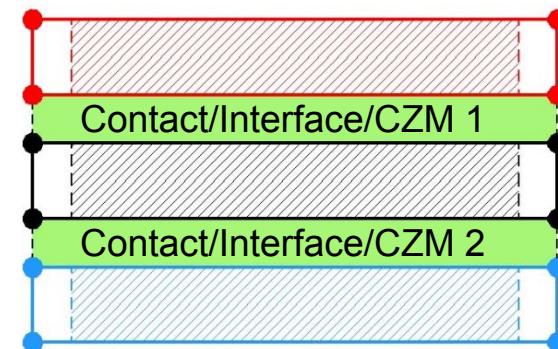
Layered Properties



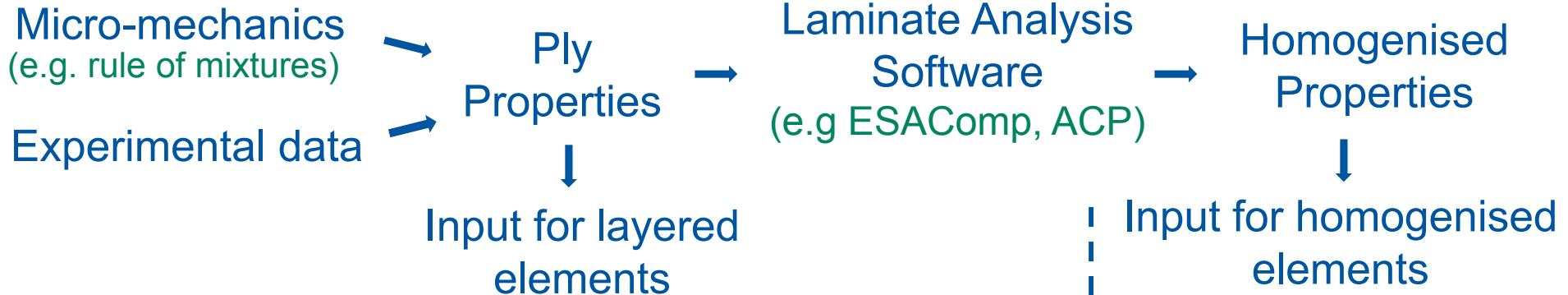
Possible to use up to one element per ply!!

Bonded or connected via interface elements to simulate delamination

- ANSYS Layered elements:
 - Shell: 181, 208, 209, 281...
 - Solid: 185, 186, 190...

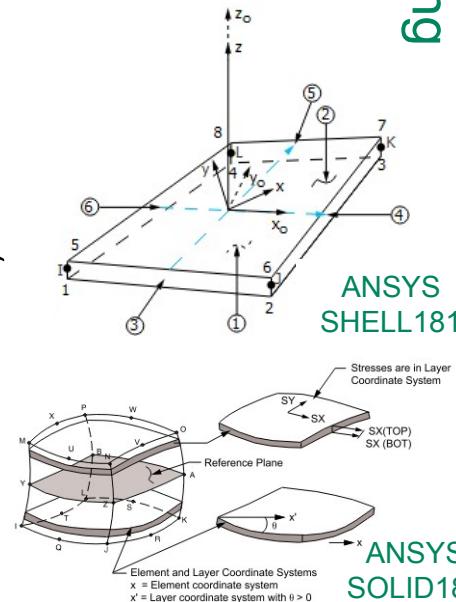
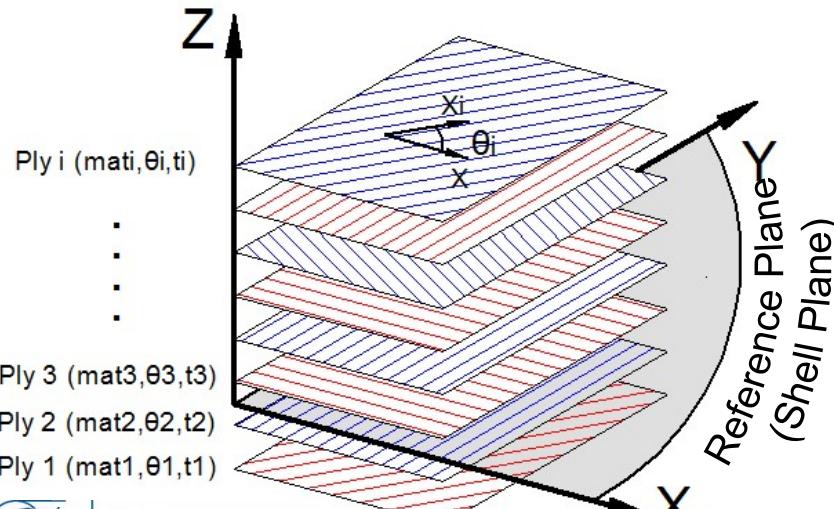


Laminates: Material Input



- Required input for layered elements

- Ply material (moduli, v_{ij} , strength parameters,...)
- Ply thickness
- Ply orientation (fibre direction, stacking direction)



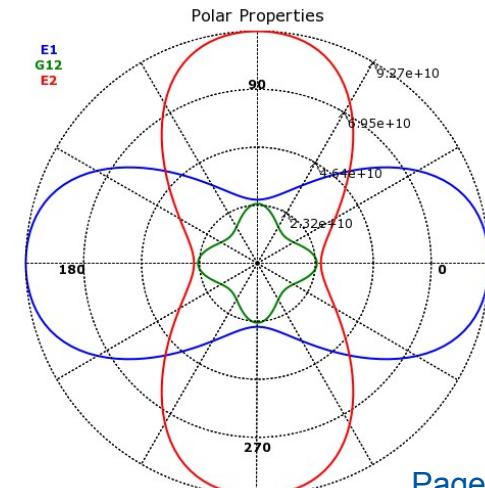
Pre-processing

Fabric.2, a=-45.0, t=0.00025
Fabric.1, a=45.0, t=0.00025
Fabric.2, a=0.0, t=0.00025
Fabric.1, a=0.0, t=0.00025
Fabric.2, a=0.0, t=0.00025
Fabric.1, a=0.0, t=0.00025
Fabric.2, a=45.0, t=0.00025
Fabric.1, a=-45.0, t=0.00025

Stackup
(ply,θ,t)

Flexural Laminate Shear Stiffness	3.4932e+10
Flexural Laminate Stiffness E1	3.67969e+10
Flexural Laminate Stiffness E2	2.50377e+10
Laminate Shear Stiffness	2.37787e+10
Laminate Stiffness E1	9.27212e+10
Laminate Stiffness E2	2.53949e+10
Out of Plane Shear G23	4.71348e-05
Out of Plane Shear G31	3.86716e-05
Shear Correction Factor k44 (G23)	0.735303
Shear Correction Factor k55 (G31)	0.727027

Laminate
Engineering
Constants



Composites Pre-processing: ANSYS WB Mechanical

Good for relatively simple geometries in which the fibre directions can be easily defined with cartesian or cylindrical coordinate system

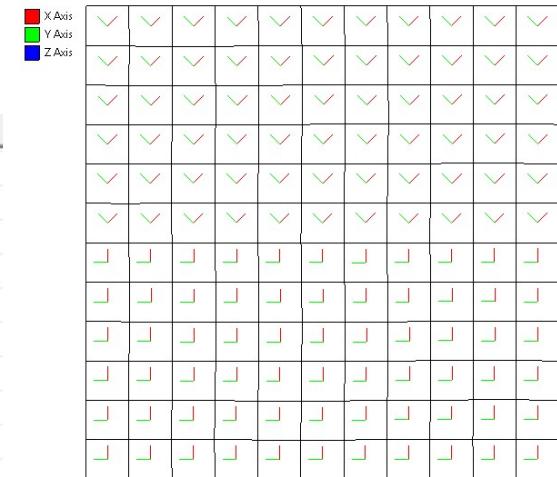
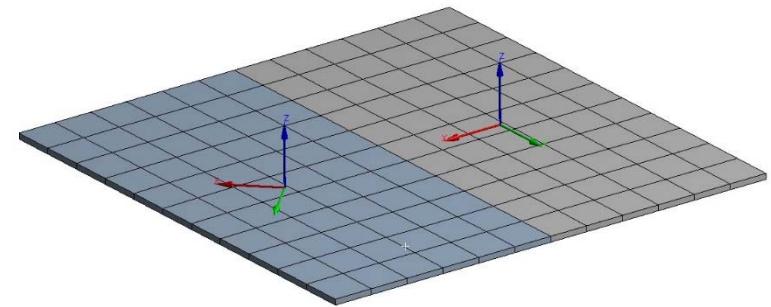
1. Material definition (plies or homogenised sub-laminates)
2. Definition of coordinate systems to define ply orientation
(The assigned material properties will follow the resulting element coordinate system)
3. Define Layer Sections (relevant area, coordinate system, ply material, thickness, angle)

Contents of Engineering Data		
Material	Description	
Honeycomb Core		
Ply 1: Epoxy1/CarbonUD_1		
Ply 2: Epoxy2/CarbonUD_2		
Click here to add a new material		
Outline Row 4: Ply 1: Epoxy1/CarbonUD_1		
A	B	C
Property	Value	Unit
Density	1490	kg m^-3
Orthotropic Secant Coefficient of Thermal Expansion		
Coefficient of Thermal Expansion		
Coefficient of Thermal Expansion X direction	-4.7E-07	K^-1
Coefficient of Thermal Expansion Y direction	3E-05	K^-1
Coefficient of Thermal Expansion Z direction	3E-05	K^-1
Reference Temperature	293.15	K
Orthotropic Elasticity		
Young's Modulus X direction	1.21E+11	Pa
Young's Modulus Y direction	8.6E+09	Pa
Young's Modulus Z direction	8.6E+09	Pa
Poisson's Ratio XY	0.27	
Poisson's Ratio YZ	0.4	
Poisson's Ratio XZ	0.27	
Shear Modulus XY	4.7E+09	Pa
Shear Modulus YZ	3.1E+09	Pa
Shear Modulus XZ	4.7E+09	Pa
Field Variables		
Orthotropic Stress Limits		
Orthotropic Strain Limits		
Tsai-Wu Constants		
Puck Constants		
Ply Type		
Additional Puck Constants		

Model (B4)

- Geometry
 - SandwichPlate
 - Plate.1
 - Plate.2
 - Layered Section Plate 1
 - Layered Section Plate 2
- Coordinate Systems
 - Global Coordinate System
 - CS_1
 - CS_2

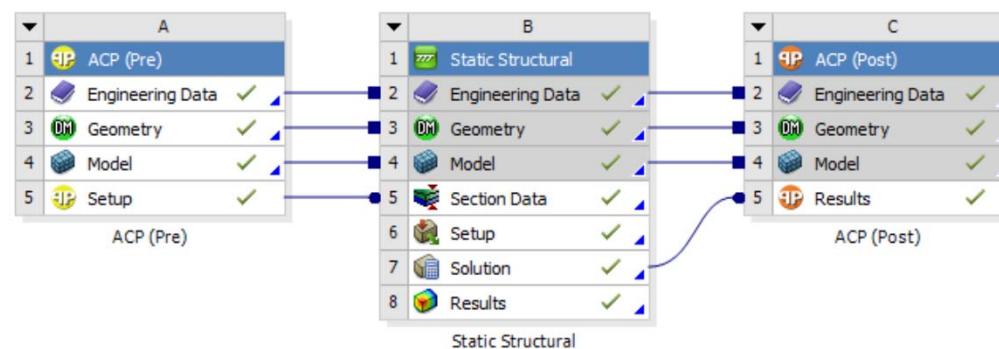
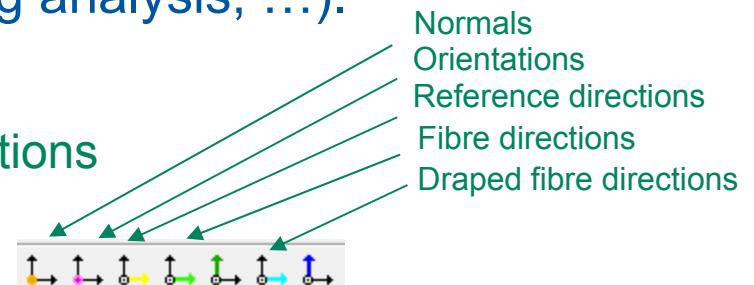
Layer	Material	Thickness (mm)	Angle (°)
(+Z)			
7	Ply1: Epoxy1/CarbonUD_1	0.2	-60
6	Ply1: Epoxy1/CarbonUD_1	0.2	0
5	Ply1: Epoxy1/CarbonUD_1	0.2	60
4	Honeycomb Core	10.8	0
3	Ply2: Epoxy2/CarbonUD_2	0.2	60
2	Ply2: Epoxy2/CarbonUD_2	0.2	0
1	Ply2: Epoxy2/CarbonUD_2	0.2	-60
(-Z)			



Difficult to define the correct element coordinate systems for complex parts/layups

Composites Modelling: ANSYS ACP

- ANSYS Composite PrePost (EVEN – Evolutionary Engineering AG)
 - ↳ See full FREE training material at ANSYS Customer Portal
<https://support.ansys.com/portal/site/AnsysCustomerPortal>
- Simplify Pre- and Post-processing of composite models
 - Integrated in WB
 - Intuitive definition of layup
 - Modelling process follows manufacturing process definition
 - Post-processing allows detailed failure analysis (ply-by-ply if needed)
- Extended functionality (fibre directions, draping analysis, ...).
- Facilitate model checks
 - Visualization of reference, layup and fibre directions
 - “Section Cut” & “Sampling Point” checks



ANSYS ACP: Summary

- Material data (WB): ply data defined in “Engineering Data” module
- Geometry (WB or CAD software)
 - ACP models always starts with **shells** (solids can be extruded at a later stage)
- Mesh (WB Mechanical)
 - Named selections to define **“element sets”**
- Material assignment (ACP)
 - Solids (e.g. thick core) properties are assigned in WB Mechanical
 - Laminates
 - Fabric definition (Ply data + Ply thickness + Draping Coefficients + Drop-off and Cut-off materials)
 - Stackups/Sublaminates
 - “Rosettes”
 - “Edge Sets”
 - Element sets
 - Modelling Group/Ply → Assign material (ply or stackup, laminate) to oriented element sets
 - Extrude Solid Models
- Analysis (WB Mechanical): Assign BCs/Loads + Solve
- Post-processing (WB & ACP)
 - General post-processing (e.g. deformation, energy) in WB
 - Detailed failure analysis (ply basis) in ACP

ANSYS ACP: Material Definition & Fabrics/Stackups

WorkBench (Ply data)

Properties of Outline Row 3: Epoxy_Carbon_UD_395GPa_Prepreg		
A	B	C
Property	Value	Unit
Density	1.54E-06	kg mm^-3
Orthotropic Secant Coefficient of Thermal Expansion		
Orthotropic Elasticity		
Young's Modulus X direction	2.09E+05	MPa
Young's Modulus Y direction	9450	MPa
Young's Modulus Z direction	9450	MPa
Poisson's Ratio XY	0.27	
Poisson's Ratio YZ	0.4	
Poisson's Ratio XZ	0.27	
Shear Modulus XY	5500	MPa
Shear Modulus YZ	3900	MPa
Shear Modulus XZ	5500	MPa
Field Variables		
Orthotropic Stress Limits		
Tensile X direction	1979	MPa
Tensile Y direction	26	MPa
Tensile Z direction	26	MPa
Compressive X direction	-893	MPa
Compressive Y direction	-139	MPa
Compressive Z direction	-139	MPa
Shear XY	100	MPa
Shear YZ	50	MPa
Shear XZ	100	MPa
Field Variables		
Orthotropic Strain Limits		
Puck Constants		
Ply Type		
Additional Puck Constants		

Data for failure analysis

ACP
(Fabrics & Stackups)

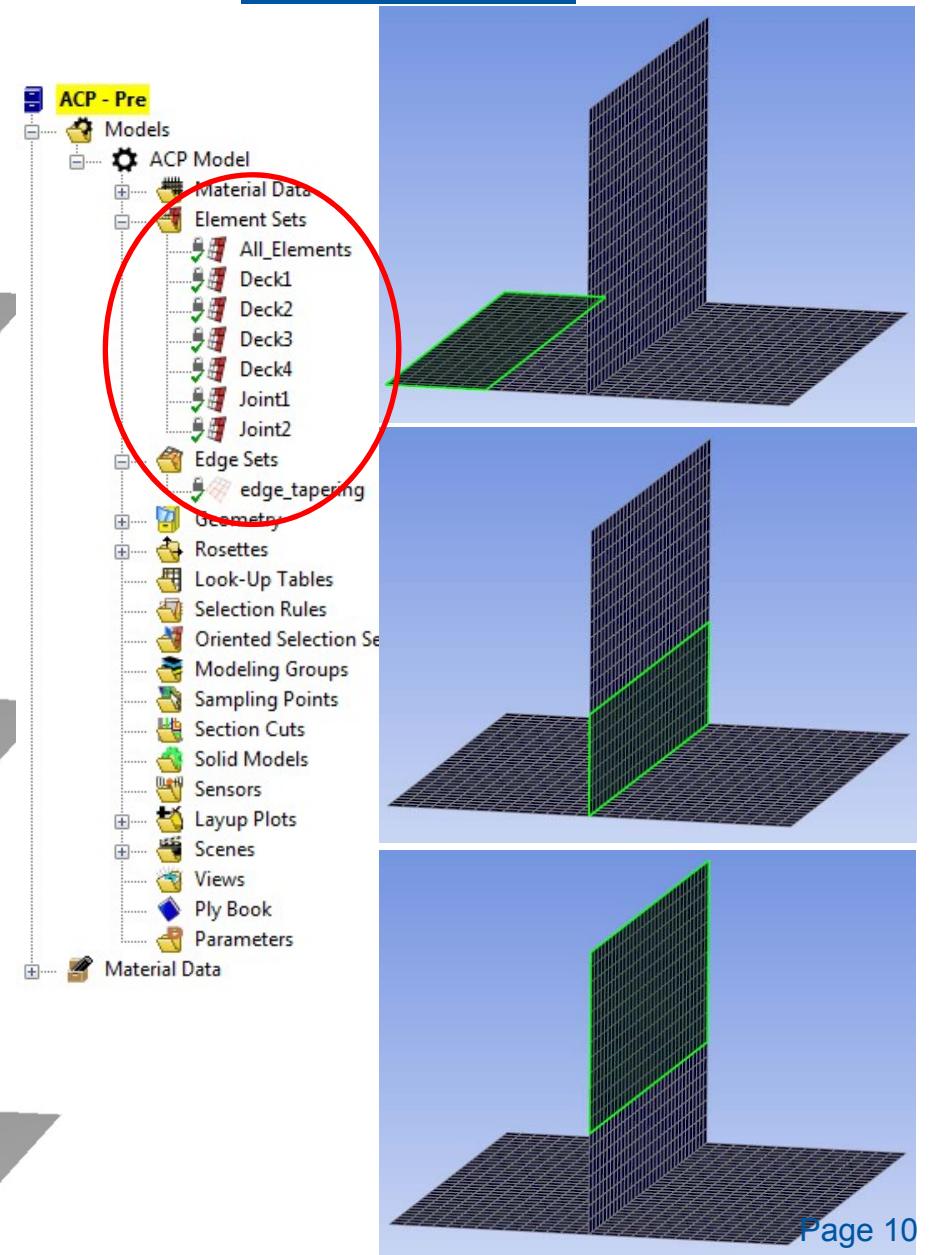
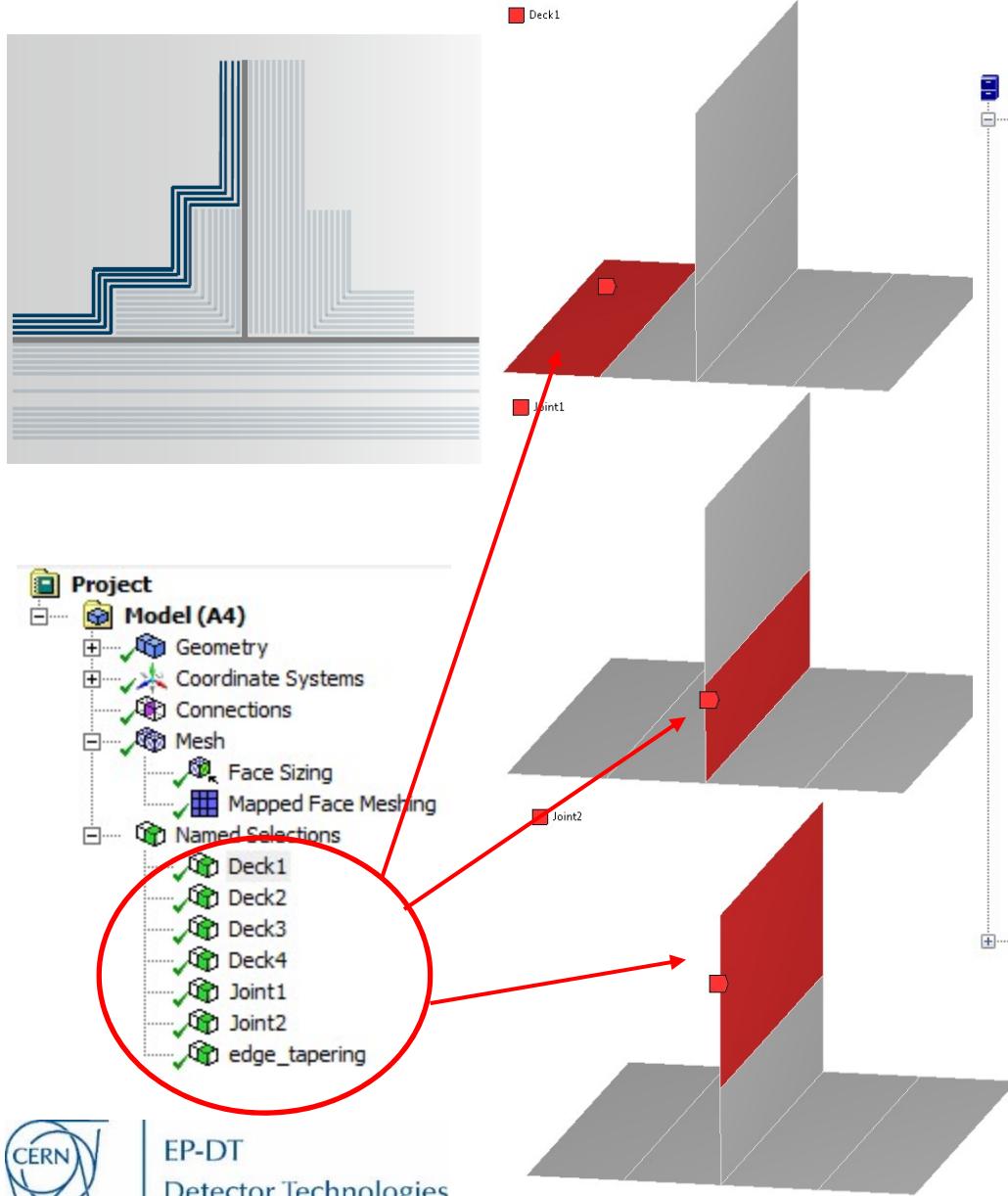
The ACP interface shows the material definition and stackup properties:

- ACP - Pre** window: Shows the ACP Model structure with Material Data, Fabrics, and Stackups.
- Fabric Properties** dialog: Shows the material Epoxy_Carbon_UD selected. The thickness is highlighted with a red circle.
- Stackup Properties** dialog: Shows the stackup Stackup.1 with a list of fabrics and their angles.
- Stackup Properties** dialog: Shows the stackup Stackup.1 AP with a polar plot of the stackup properties.



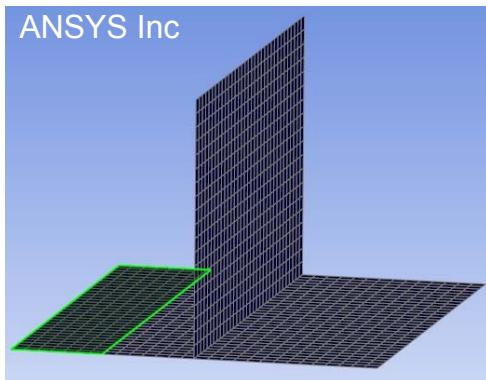
ANSYS ACP: Geometry & Mesh

- WB: Named selections to define layup areas → Element Sets

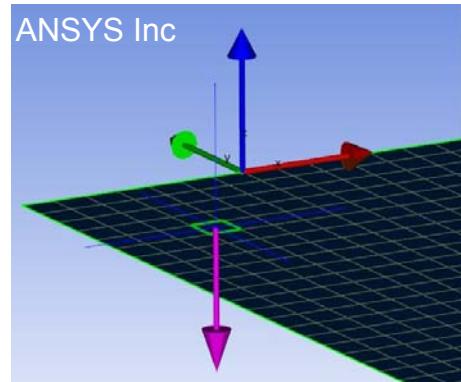


ANSYS ACP: Material Assignment

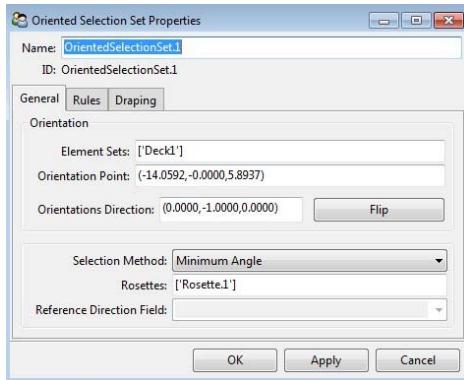
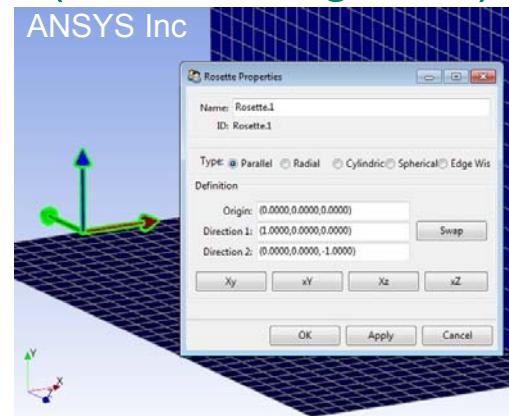
Layup area
(Element Set)



Layup direction

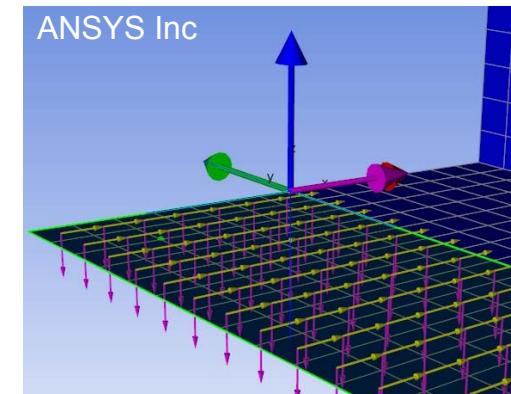


Reference direction
(Rosette/edge Set)

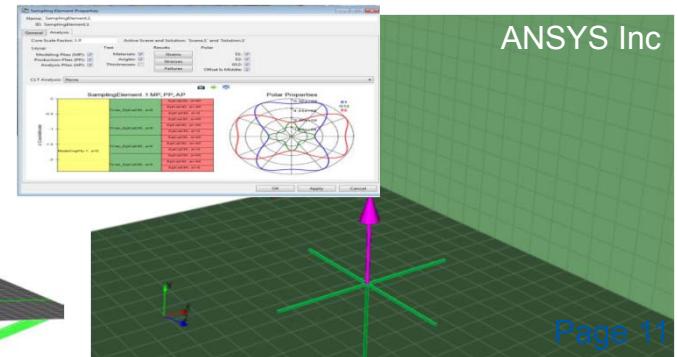
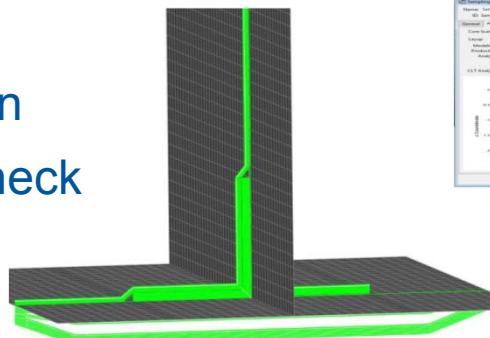


Oriented Element set

↓
Material assignment
(Layup: fabrics/stackups)

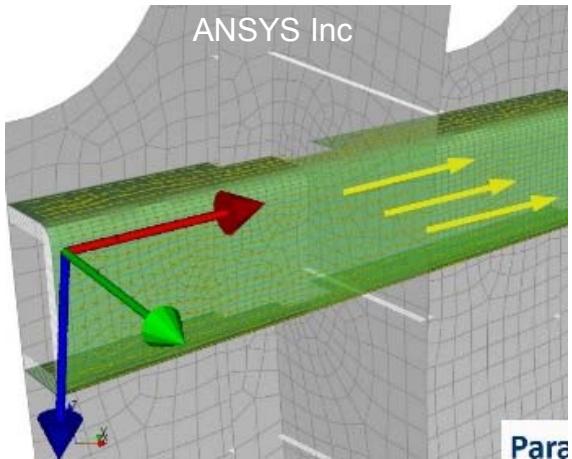


- Section Cuts → Visual verification
- Sampling Points → Properties check

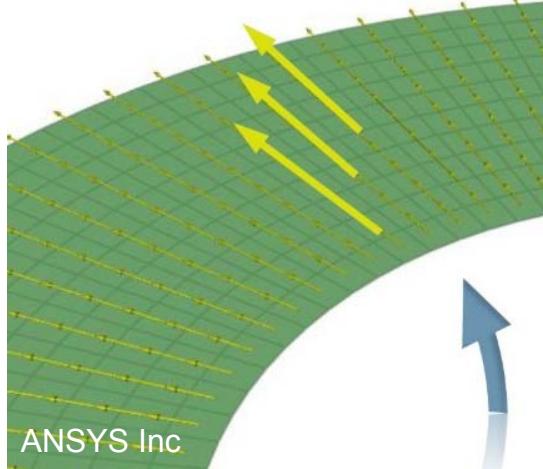


ANSYS ACP: Rosettes

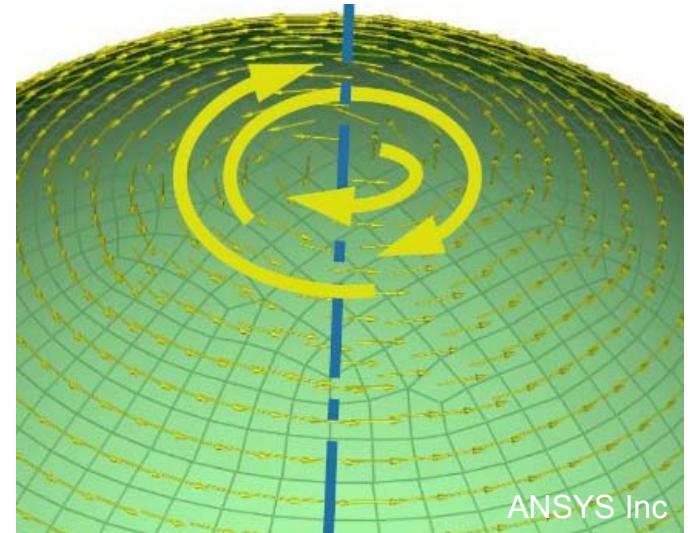
- Coordinate systems used to define reference directions (x-axis=0° fibre directions)



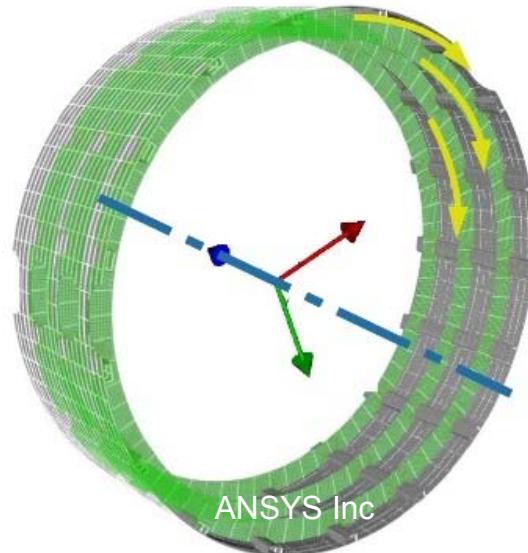
Parallel



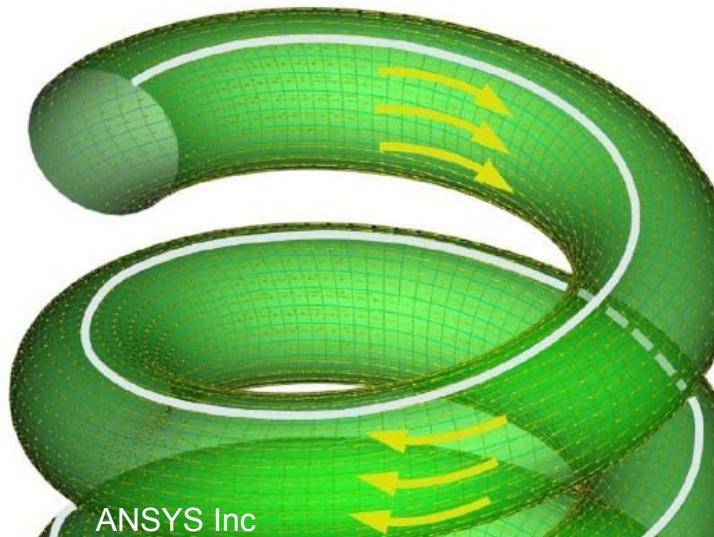
Radial



Spherical



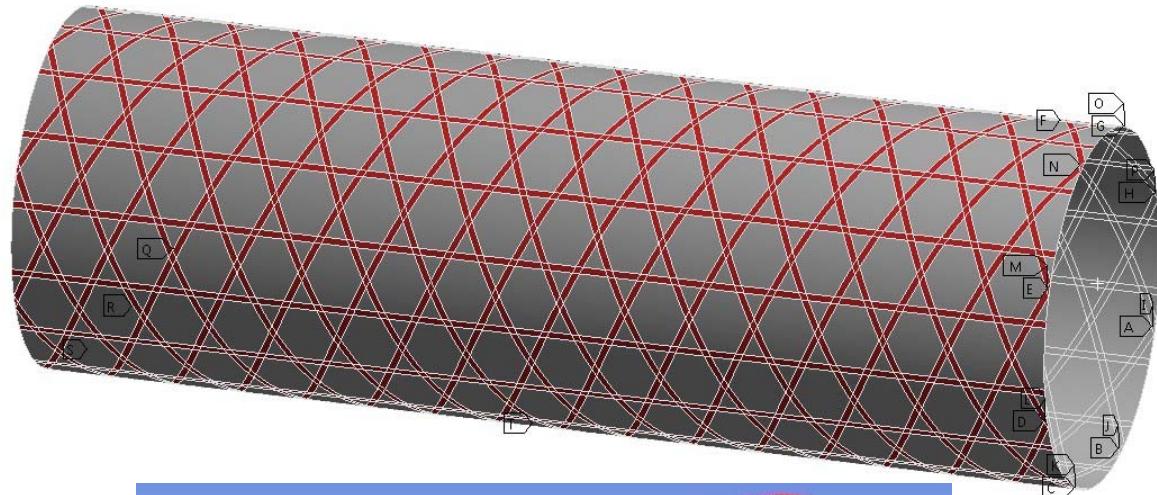
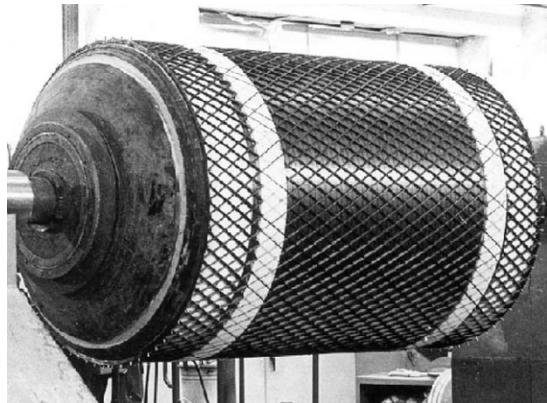
Cylindrical



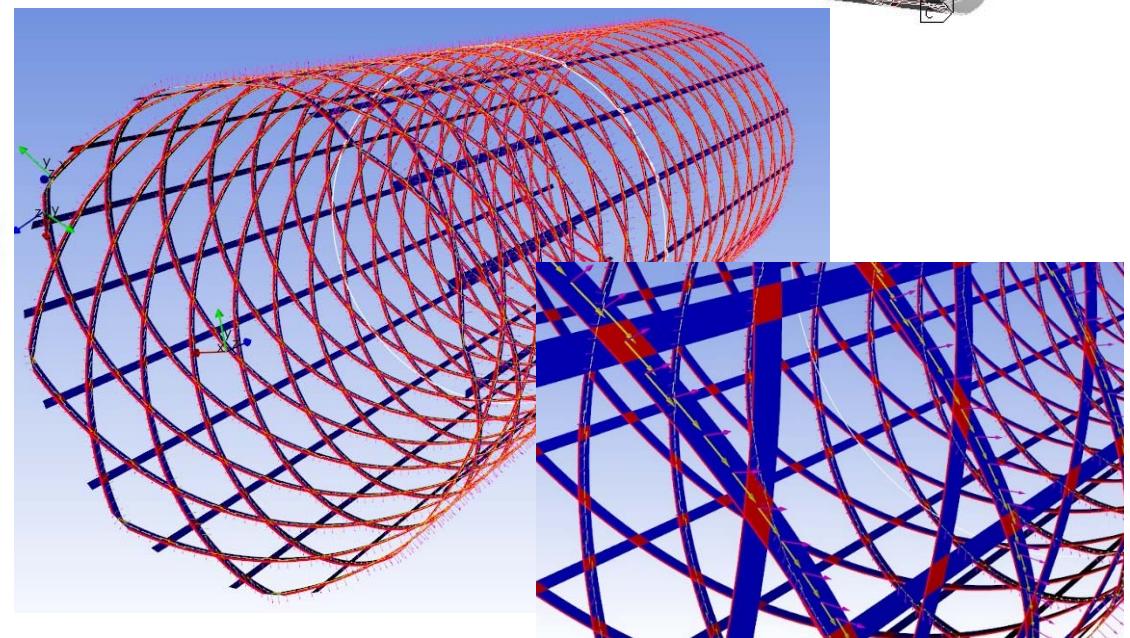
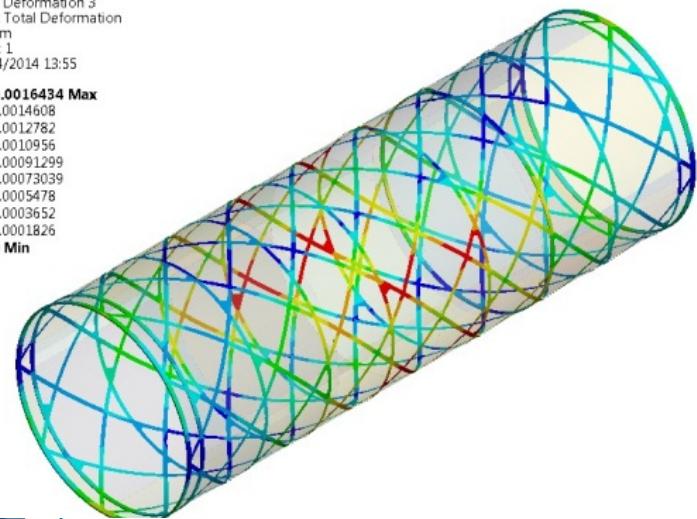
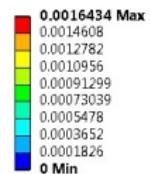
Edge-wise (edge set)

ACP Example: CFRP Cylindrical Iso-grid

- Feasibility study for ATLAS ITK Outer Cylinder
- Edge-wise rosette to define fibre direction in the hoop, helicoidal reinforcements



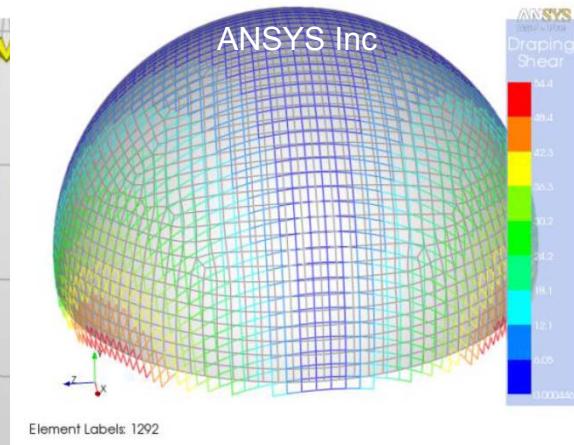
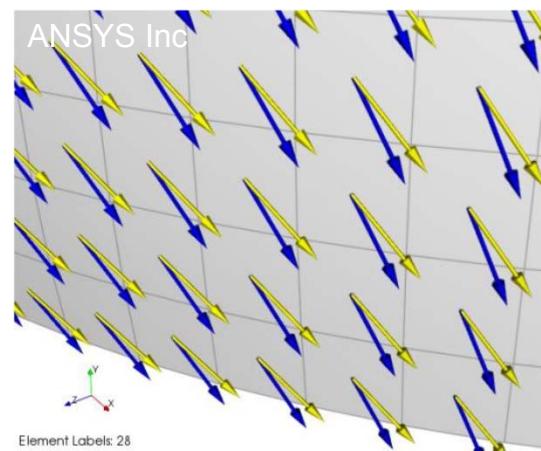
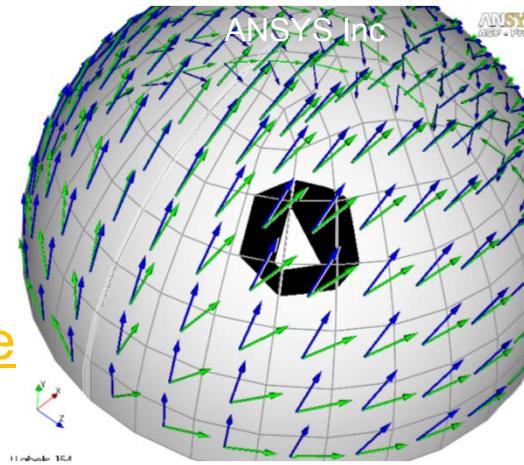
C: Static Structural
Total Deformation 3
Type: Total Deformation
Unit: m
Time: 1
07/04/2014 13:55



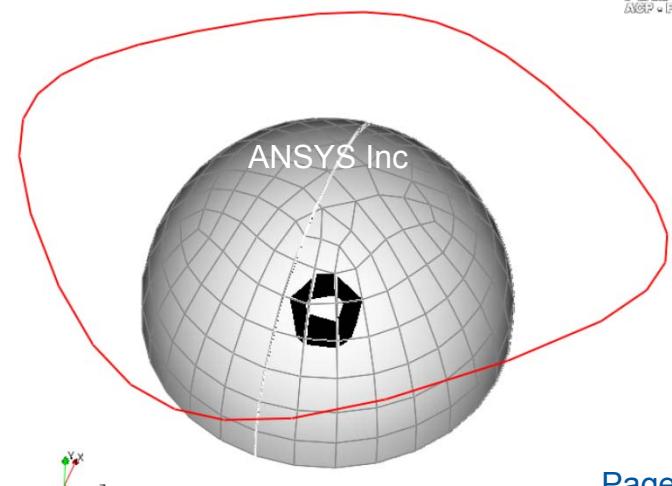
ANSYS ACP: Draping

- Draping: placing layers into a form → Wrinkling effects (curvature)
↳ Distortion in fibre directions due to draping
- ACP can be used to analyse draping effects and to correct the fibre directions
 - User-selected pin point + Minimum shear strain energy

Fibre
Draping
Reference

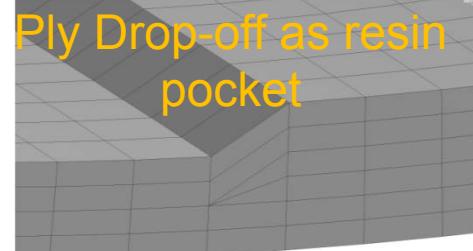
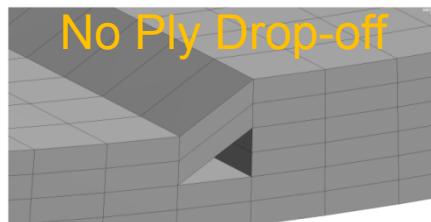
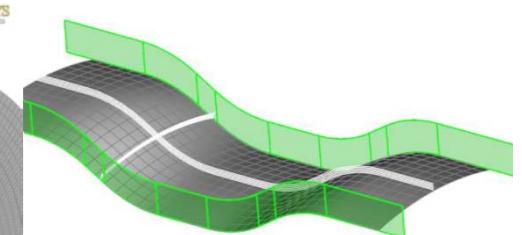
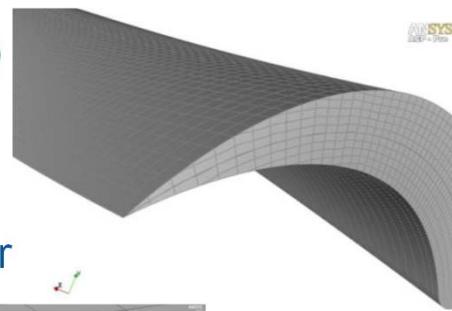
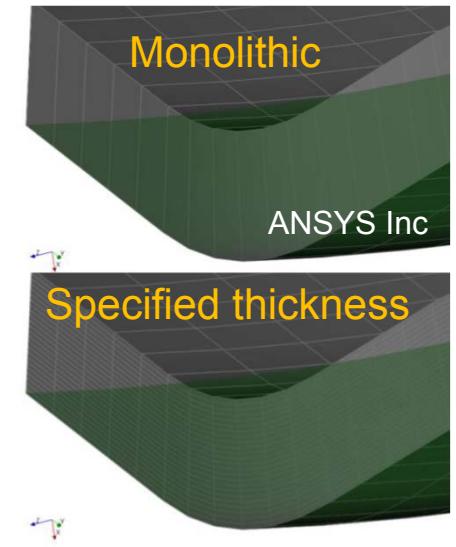
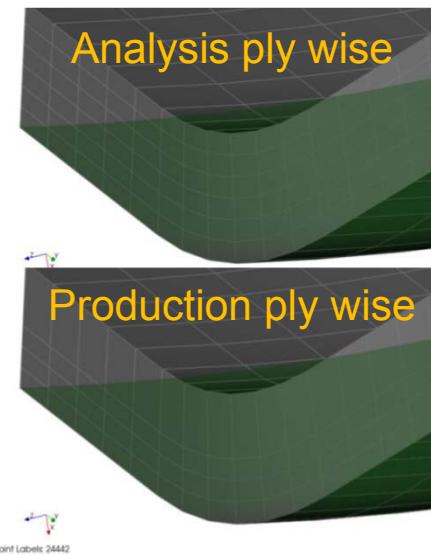
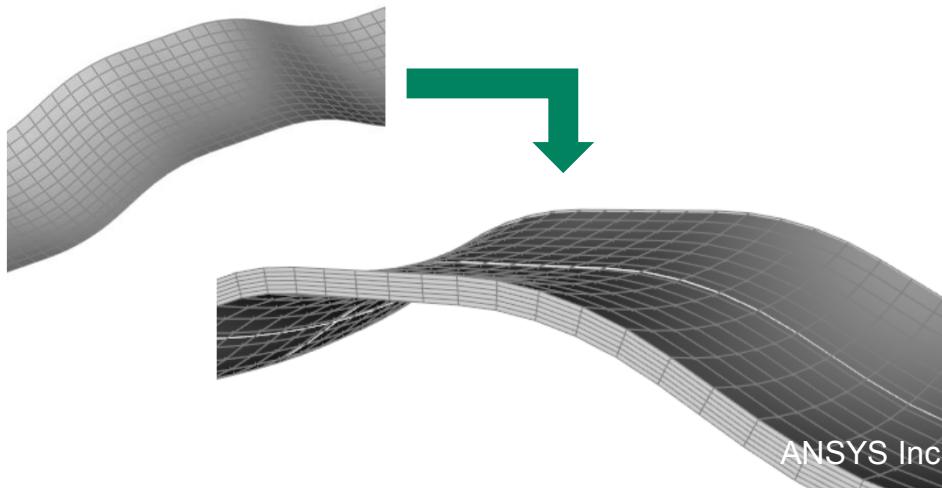


- Flatwrap to see the area of fabric needed to manufacture the design under study
(possible to export it as .dxf file)



ANSYS ACP: Solids

- Significant through thickness or out-of-plane shear stresses
- **ACP: Solids are extruded from shell using layup information**



ANSYS ACP: Post-processing & Failure Analysis

- Failure Criteria (add to “Definitions”):

- Max. Strain & Max. Stress
- Tsai-Wu
- Tsai-Hill
- Hashin
- Puck
- Cuntze
- LaRC
- Face Sheet Wrinkling
- Core Failure

To be switched to
3D for solid
models

Reserve Factor

$$RF = \frac{\text{Ultimate Strength}}{\text{Ultimate Load}} \begin{cases} < 1 & \text{Failure} \\ > 1 & \text{Safe} \end{cases}$$

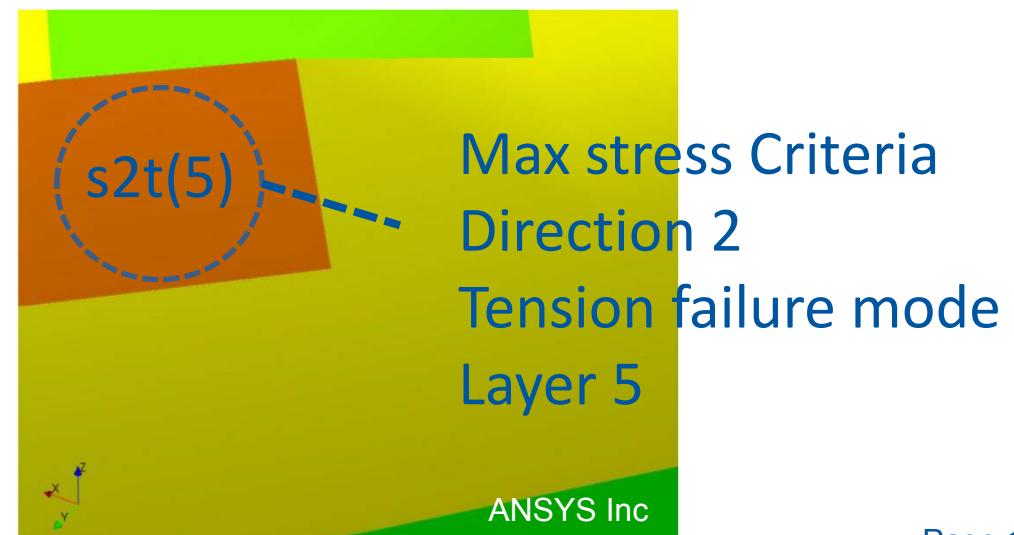
Inverse Reserve Factor

$$IRF = \frac{\text{Ultimate Load}}{\text{Ultimate Strength}} \begin{cases} > 1 & \text{Failure} \\ < 1 & \text{Safe} \end{cases}$$

Possible to evaluate all the criteria simultaneously, layer by layer

- Single failure overview plot

- Failure criteria
- Failure Mode
- Critical Layer
- Critical load step



Layered Composites: Modelling Delamination

- Composites: Inter-laminar crack between two adjacent plies
- Similar failure mechanisms to those in adhesively bonded joints (interfacial & cohesive failure)

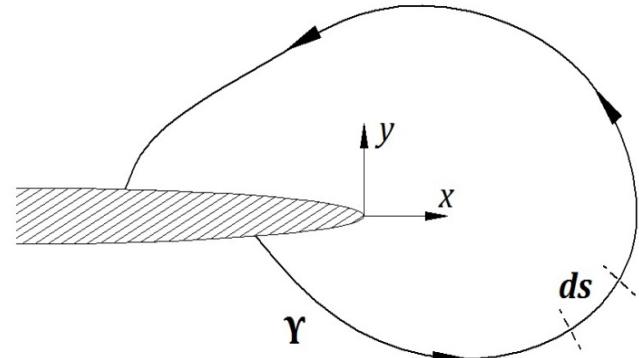


- Nucleation & propagation of cracks → **Fracture Mechanics**
 - Analysis techniques for delamination/crack modelling:
 - J-Integral
 - Virtual Crack Closure Technique (VCCT)
 - Cohesive Zone Modelling (CZM)
 - eXtended Finite Element Method (XFEM)
- } Fracture tool in ANSYS WB

J-Integral

- Rice (1968):

$$J = -\frac{\partial \Pi}{\partial A} \rightarrow J = \int_Y \left(W dy - \mathbf{T} \cdot \frac{d\mathbf{u}}{dx} ds \right)$$



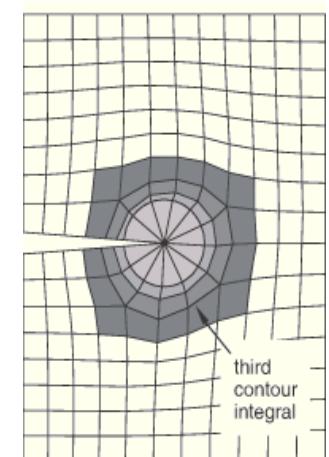
- Characterize crack tip conditions in non-linear elastic materials

- Under LEFM: $J = G_I + G_{II} + G_{III}$

- Contour dependent in FE? \rightarrow Mesh Sensitivity \rightarrow

- Problematic for crack propagation analysis

- Requires initial crack (No nucleation)
 - Refined mesh around crack tip
 - Problems in 3D and unloading (non-linear elastic material assumption)

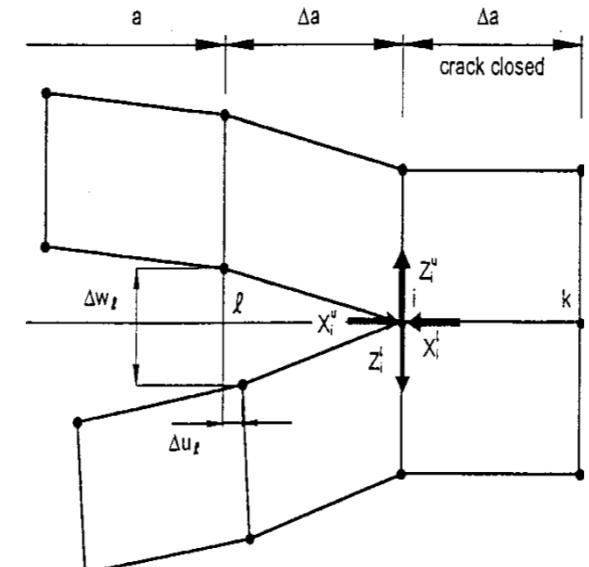


From: ABAQUS
User's Manual

Virtual Crack Closure Technique (VCCT)

- Hypothesis:
 - Energy to grow crack $\Delta a \approx$ Energy to close crack Δa
 - Stress field by crack growth Δa is unchanged
- Compute strain energy release rate (G)

$$G_I = \frac{1}{2B\Delta a} Z_i \cdot \Delta w_l \quad G_{II} = \frac{1}{2B\Delta a} X_i \cdot \Delta u_l$$

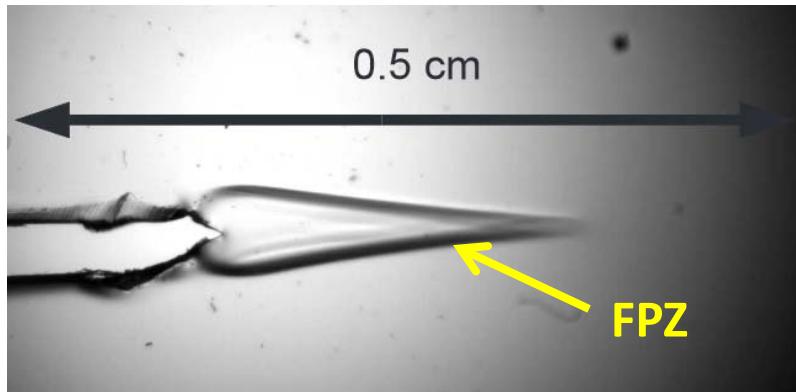


From: Krueger (2002), NASA

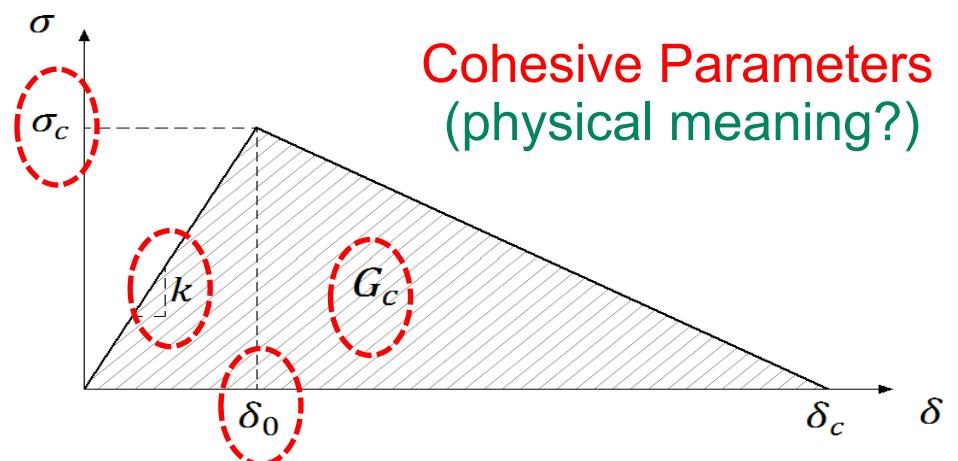
- Crack propagation analysis $\left(\frac{G_I}{G_{Ic}}\right)^\alpha + \left(\frac{G_{II}}{G_{IIc}}\right)^\beta + \left(\frac{G_{III}}{G_{IIIc}}\right)^\gamma = 1$
 - Pre-defined crack propagation path
 - No crack nucleation
 - LEFM ——> Assumes crack tip singularity (not always valid)
 - Propagation between dissimilar materials?

Cohesive Zone Model (CZM)

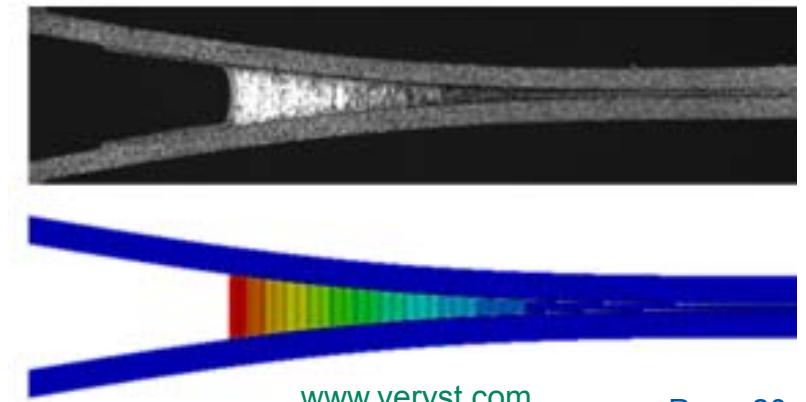
- FPZ (Dugdale, 1960) → Localized damage area
 - ↳ “Cohesive law” or “Traction-Separation law” $\sigma = \sigma(\delta)$
 - ↳ Fracture Mechanics → $G_c = \int_0^{\delta_c} \sigma \cdot d\delta$



Cortet et al. *Europhys. Lett.* (2005)



- In ANSYS & Abaqus, available as:
 - Cohesive contact
 - Interface elements



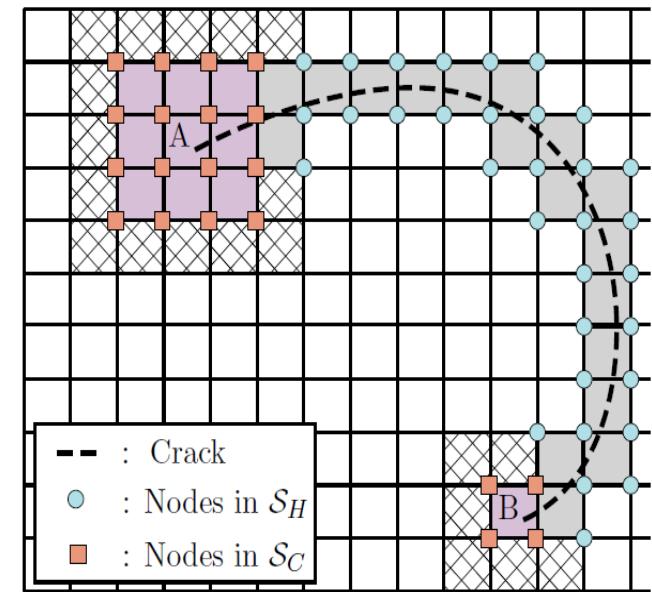
eXtended Finite Element Method (XFEM)

- Standard FE + Enrichment functions via Partition of Unity (PU)
 - Problems containing discontinuities
 - Mesh doesn't have to conform to crack geometry
 - No need for pre-defined cracked propagation path

$$\vec{u}(\vec{x}) = \underbrace{\sum_i N_i(\vec{x}) \vec{u}_i}_{\text{Standard FE}} + \underbrace{\sum_{j \in S_{cr}} N_j(\vec{x}) (H(\vec{x}) - H(\vec{x}_j)) \vec{a}_j}_{\text{Crack face enrichment}} + \underbrace{\sum_{k \in S_{tip}} \sum_{l=1}^4 N_k(\vec{x}) (\Psi_l(\vec{x}) - \Psi_l(\vec{x}_k)) \vec{b}_k^l}_{\text{Crack tip enrichment}}$$

\vec{a}_j, \vec{b}_k^l : Enrichment coefficients

- Algorithm to track the position of crack (LSM)
- Criteria for failure (stress, strain, fracture mechanics) and direction for crack propagation
- Numerical integration and element blending represent major difficulties.
- Introduced in ANSYS APDL v16 (available in Abaqus since 6.9)



Summary

- The analysis scale and the geometrical representation of the laminate should be selected taking into account the analysis needs and the computational power available.
- ANSYS WB is suitable for simple composite geometries/laminates
- ANSYS ACP offers significant advantages for modelling complex composite parts
 - Pre-processing is simplified by using rosettes and oriented element sets
 - Extruded solid models yield a more realistic geometry
 - Ply failure can be analysed ply-by-ply for a various criteria
- ANSYS feature a number of fracture mechanics techniques suitable for the study of delamination in composites and de-bonding in glued joints.